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Geotechnical Aspects of Underground Options for CAES

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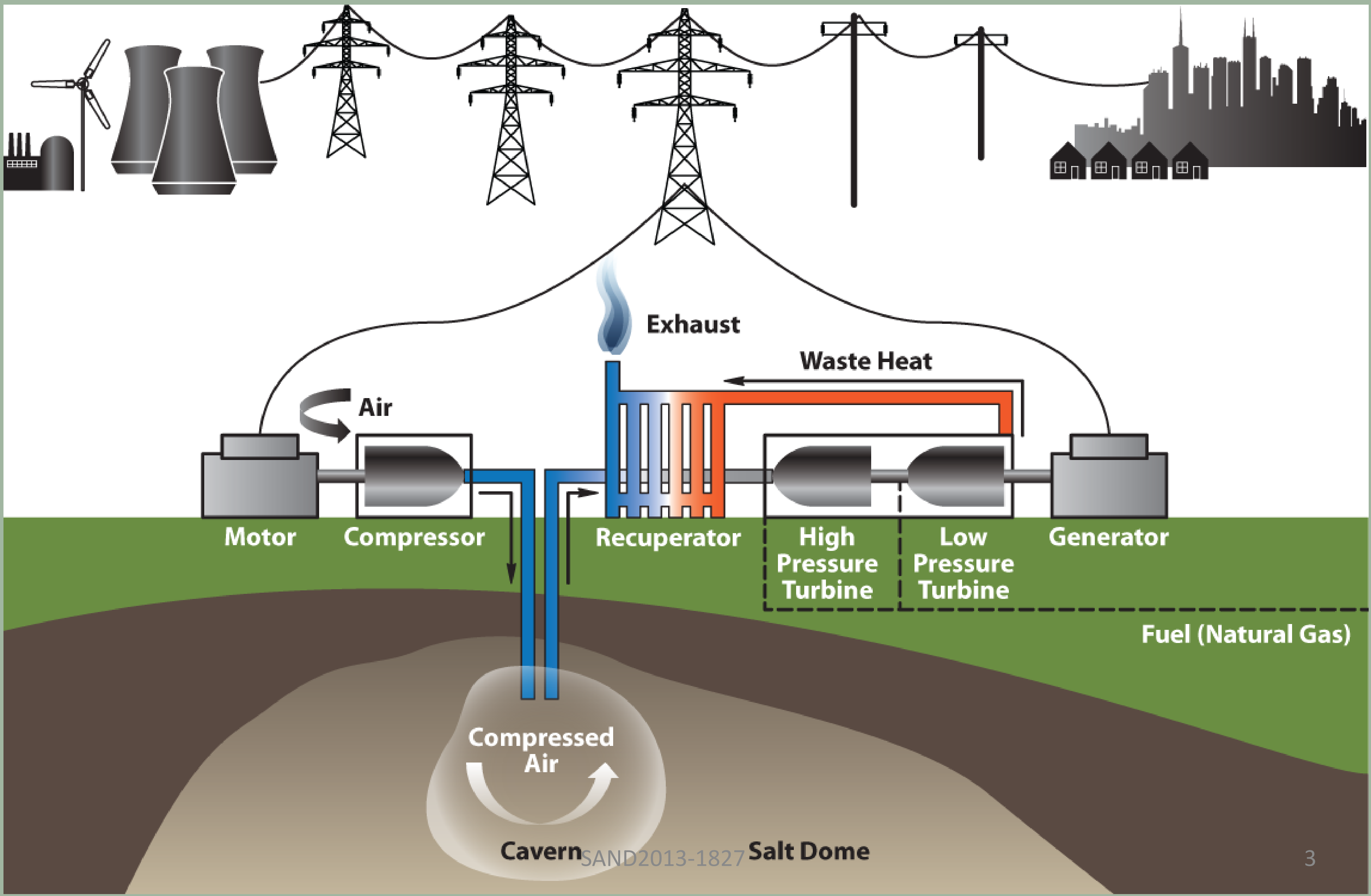
Thanks

Outline

Acknowledgements

What's it all about?



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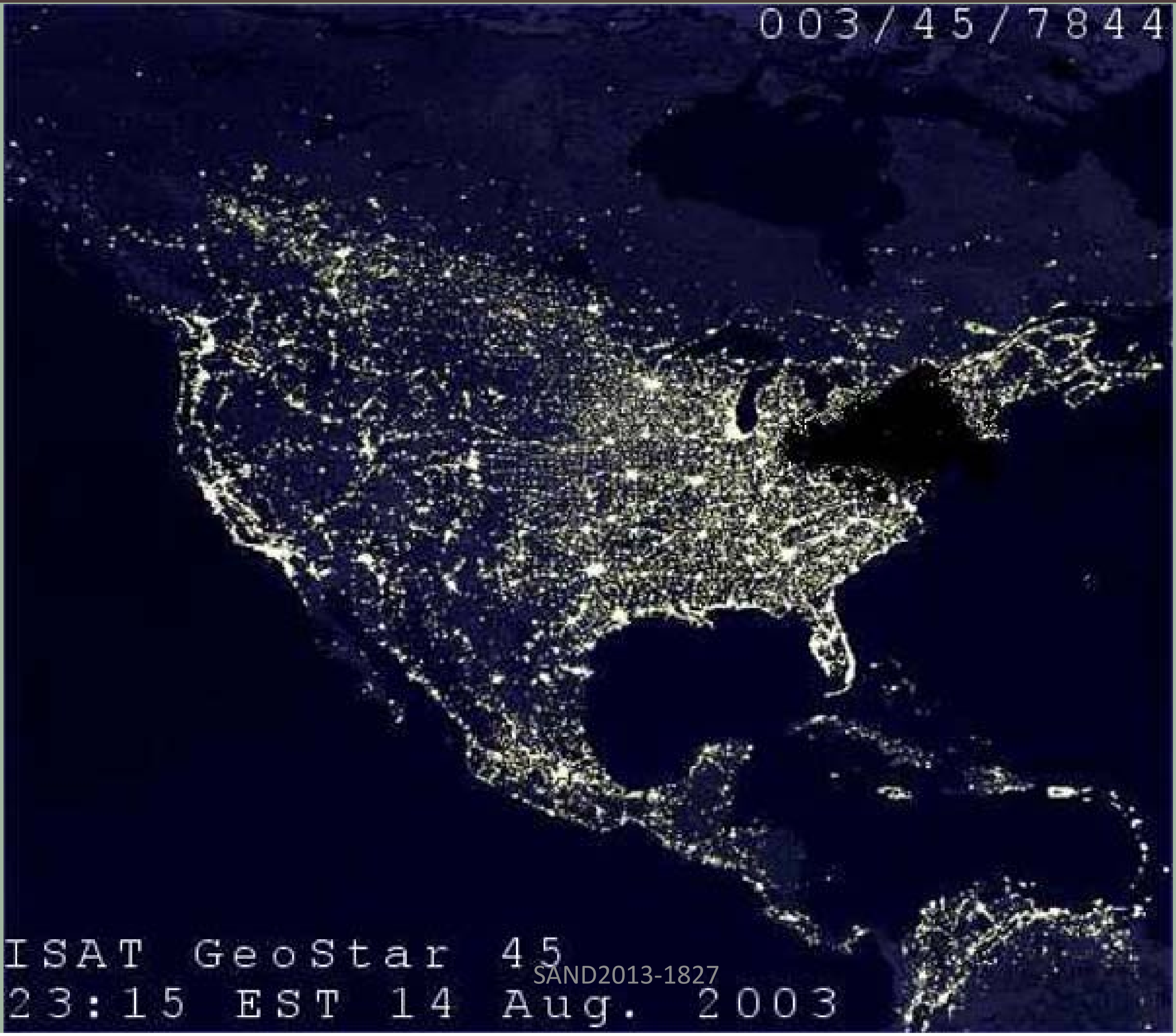
Bulk Energy Storage Impact?



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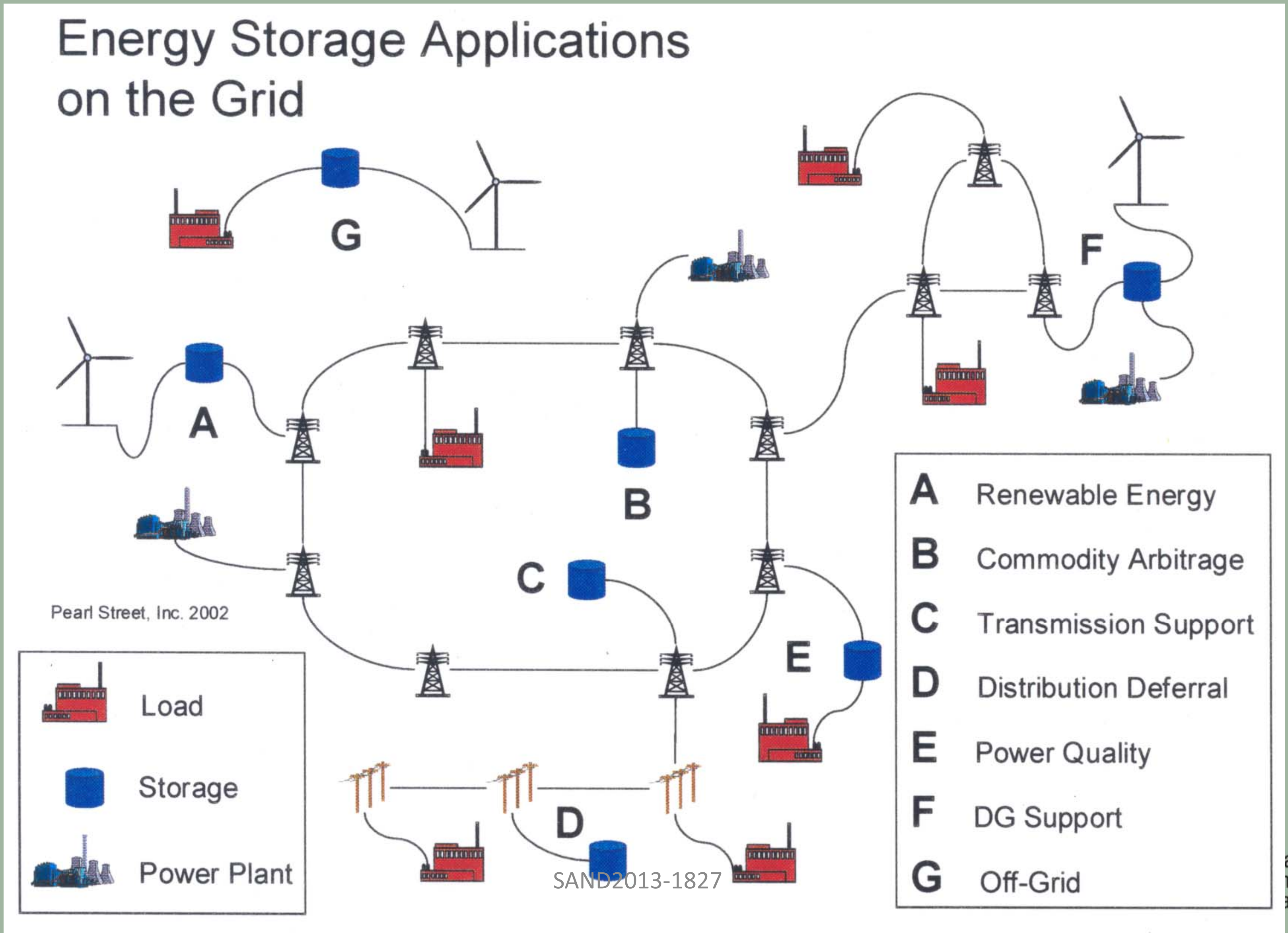
Energy storage applications on the grid

(Energy Resource Council).



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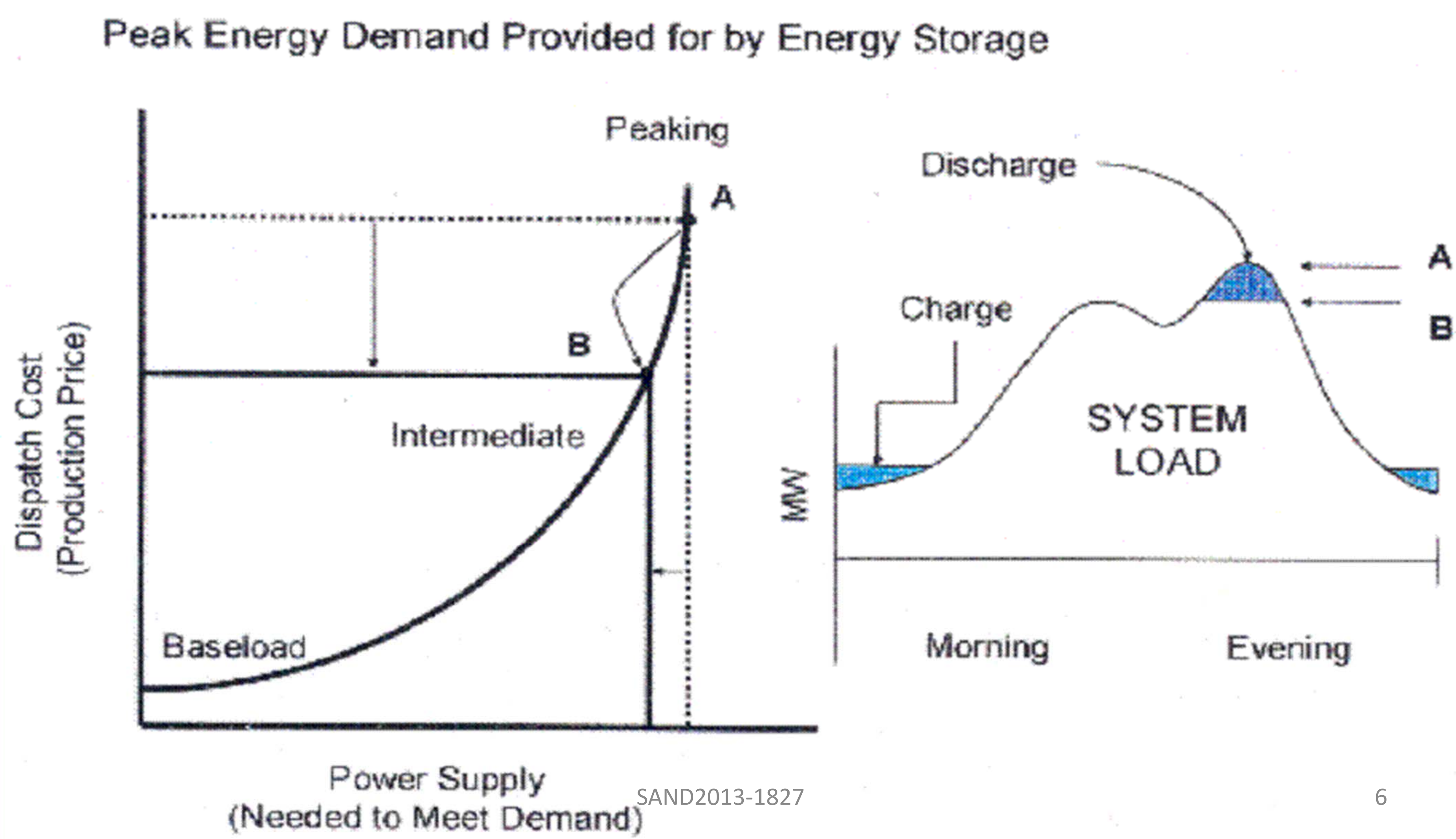
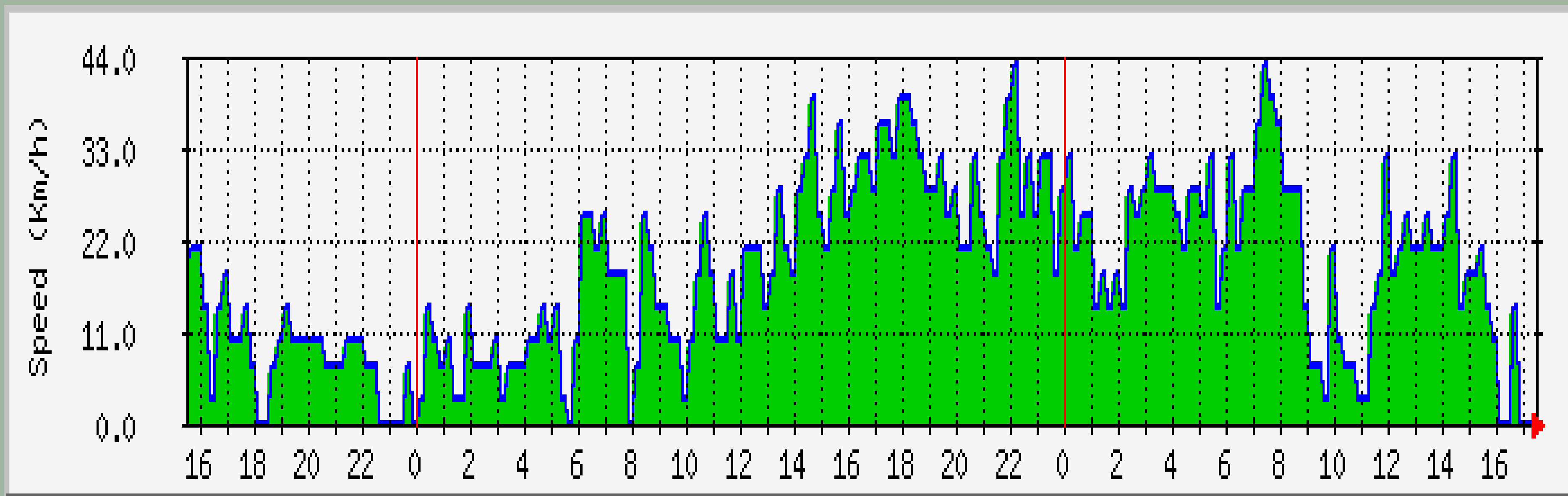
Peak energy demand provided for by energy storage

(Energy Resource Council).



Chasing Wind



Hourly fluctuations in wind speed could translate to frequent pressurization/depressurizations of underground formations

Desired Conditions

- at depth in competent rock
- well sealed container
- large volume
- can deliver air at desired rates
- favorable stress state
- can withstand pressure cycles**
- no detrimental conditions/circumstances

excel sheet

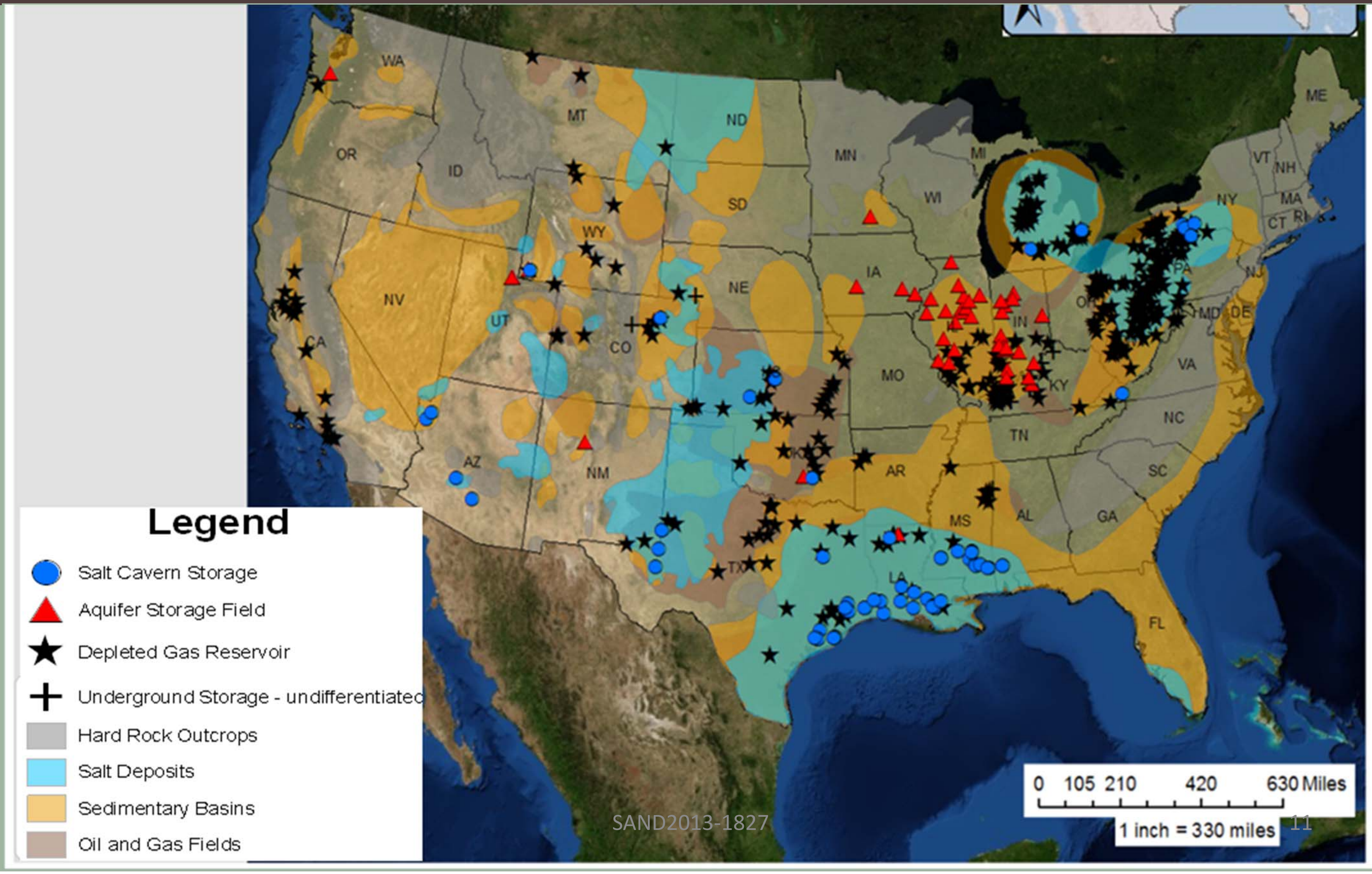
Geotechnical Feasibility

- Depth : 500 - 1500m
- Volume > 2 x10^5 m^3
- Competent structure, non-oxidizing
- *In situ* stresses compatible with desired pressures
- Favorable hydrologic conditions
- Favorable openings
- Competing circumstances

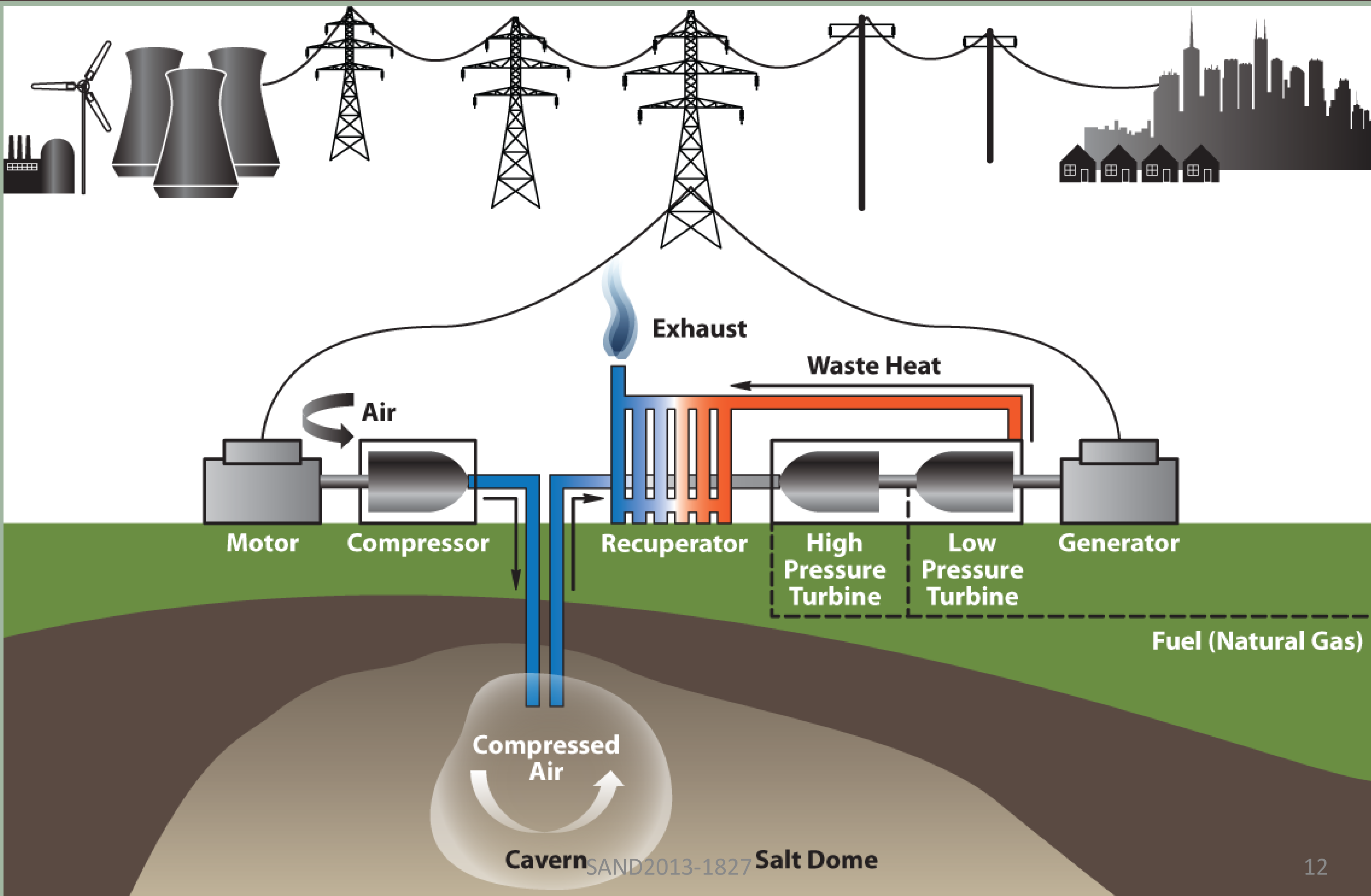
Some Geotechnical Options

- **Caverns in Salt (Engineered)**
  - (optimal depths of cavern ~2000 ft)
- **Mined cavities (lined or unlined)**
  - (Depth depends on liner (or not), water curtain)
- **Reservoirs (depleted natural gas, aquifers, fractured systems, engineered)**
  - (optimal depths ~3000 ft, K>400mD, Φ>.15)
- **Former Mines**
  - (optimal depths ~2000- 4000 ft)
- **Manmade vessels** (better if buried)

Geotechnical Locations



Salt caverns



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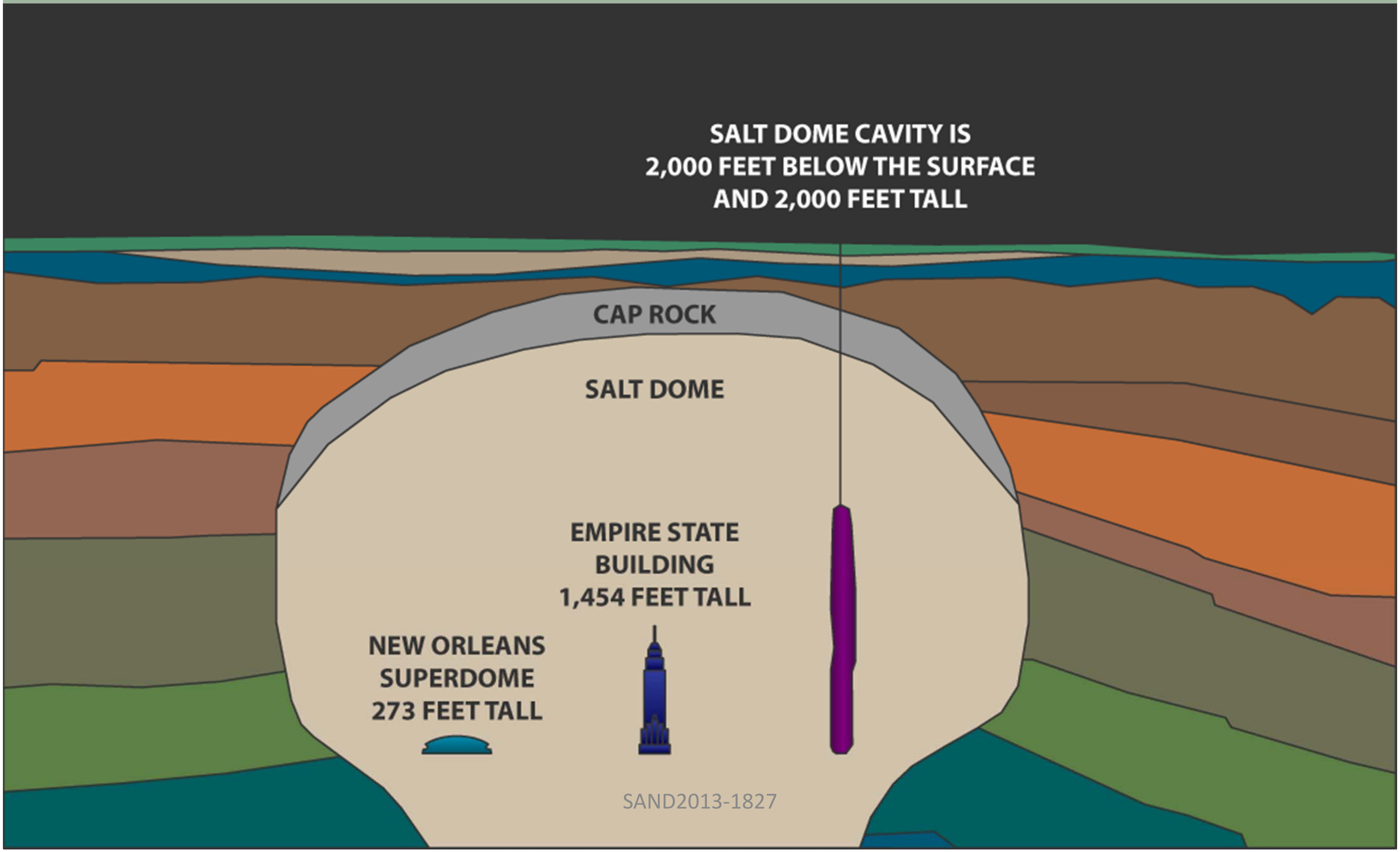
Cavern Size Comparison

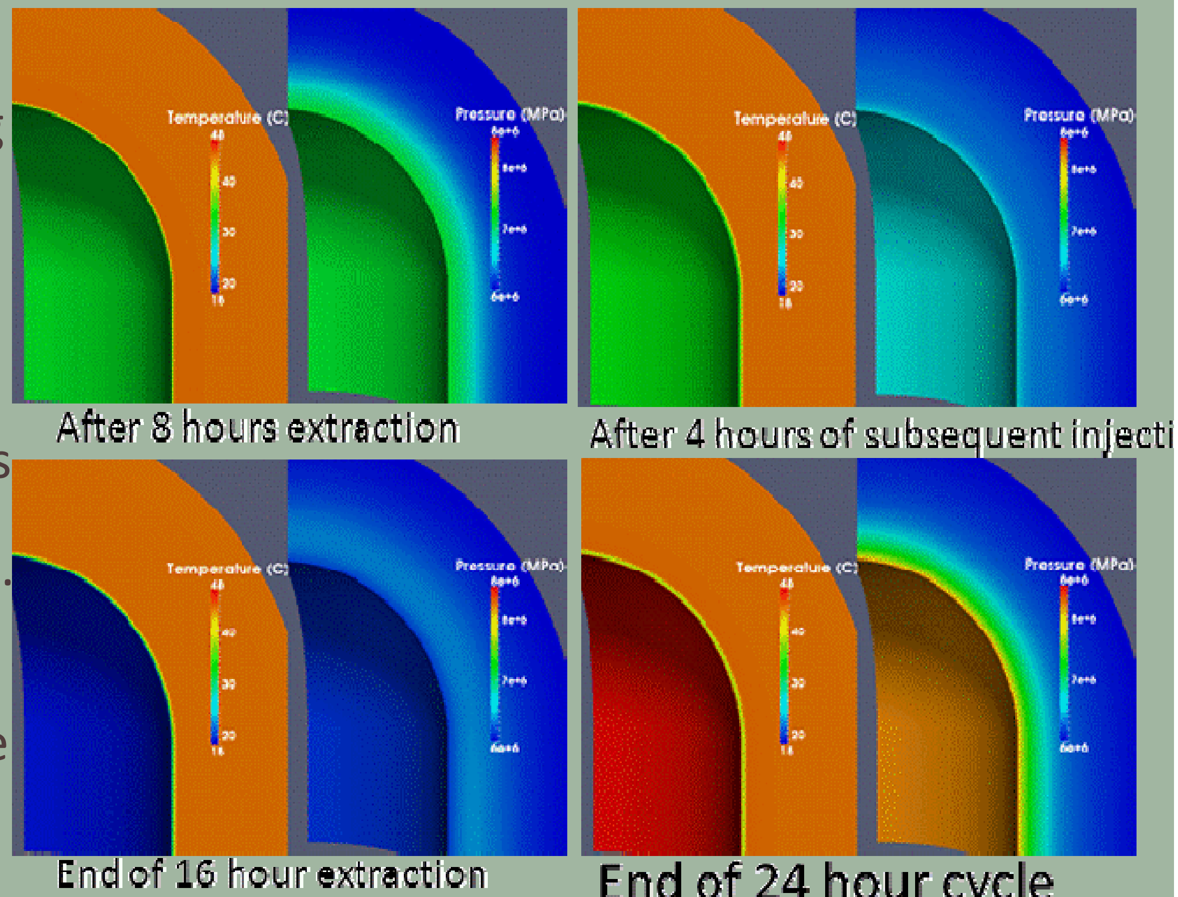


Salt caverns

- 2 Operating CAES-in salt in world
- Extensive history in NG storage
  - Include good engineering of good salt, casing, geometry
- Location, depth, cycling
- Thermomechanical effects?

Salt Caverns

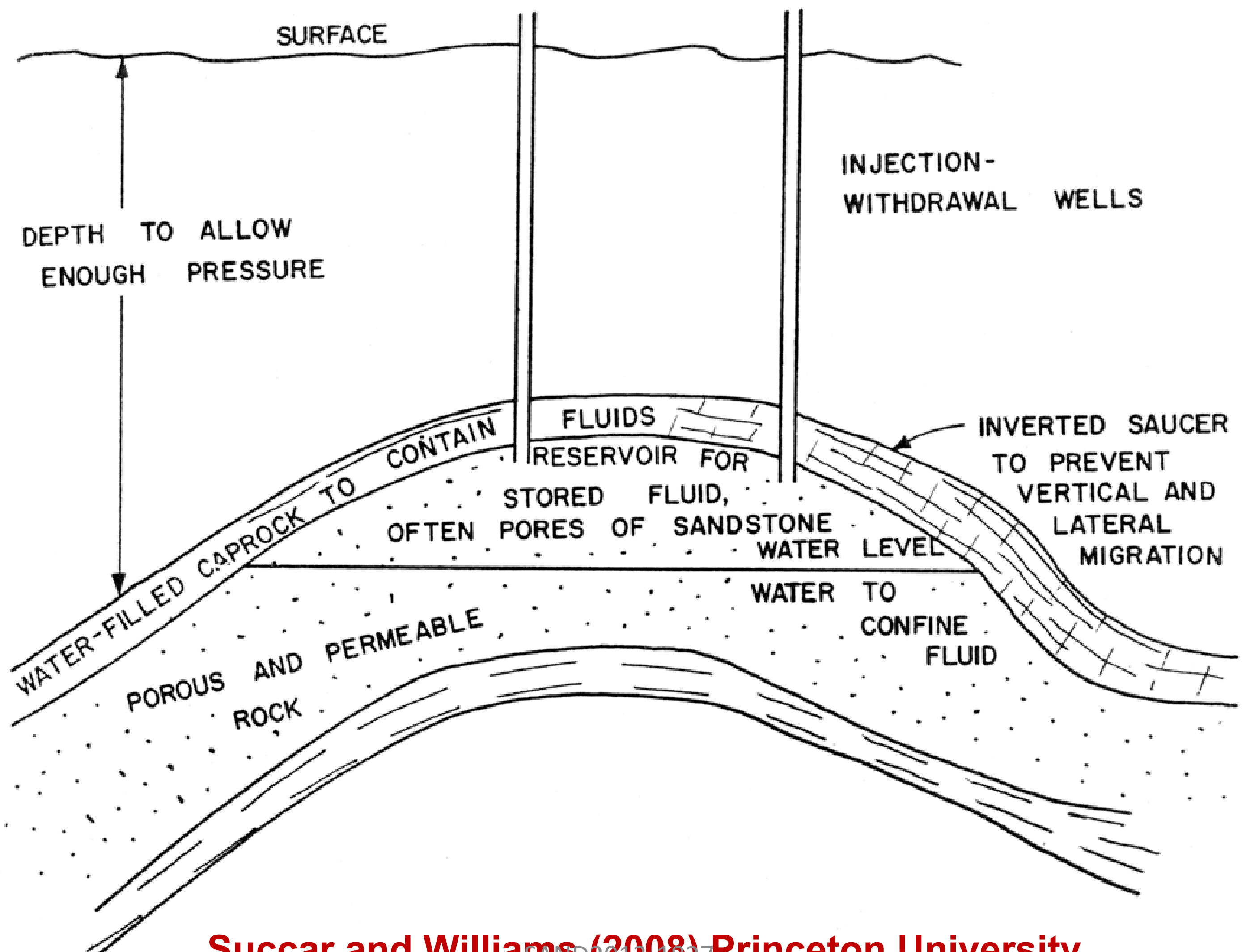
- Understanding the effects of rapid thermal/pressure cycling is crucial to assess long term performance of CAES and to assess cavern gas conditions affecting efficiency and economics.
- Cavern gas thermodynamics is coupled with energy transfer to and from the salt formation.
- The cycle-averaged cavern temperature can be chosen to minimize creep/damage of the cavern and minimize efficiency-reducing energy losses to and from the formation.



End of 24 hour cycle

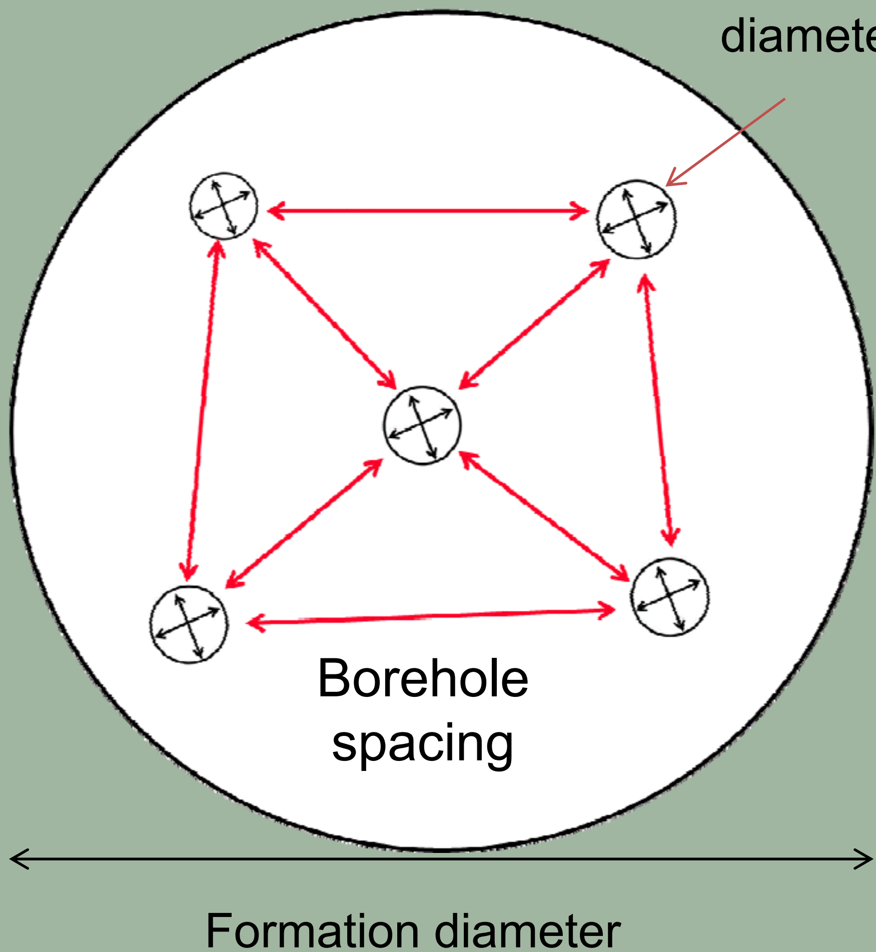
Walls are 30m thick. Cavern is made up of cylinder mids (height=65m; radius 40m) with hemispheres (radius=40m) at top and bottom

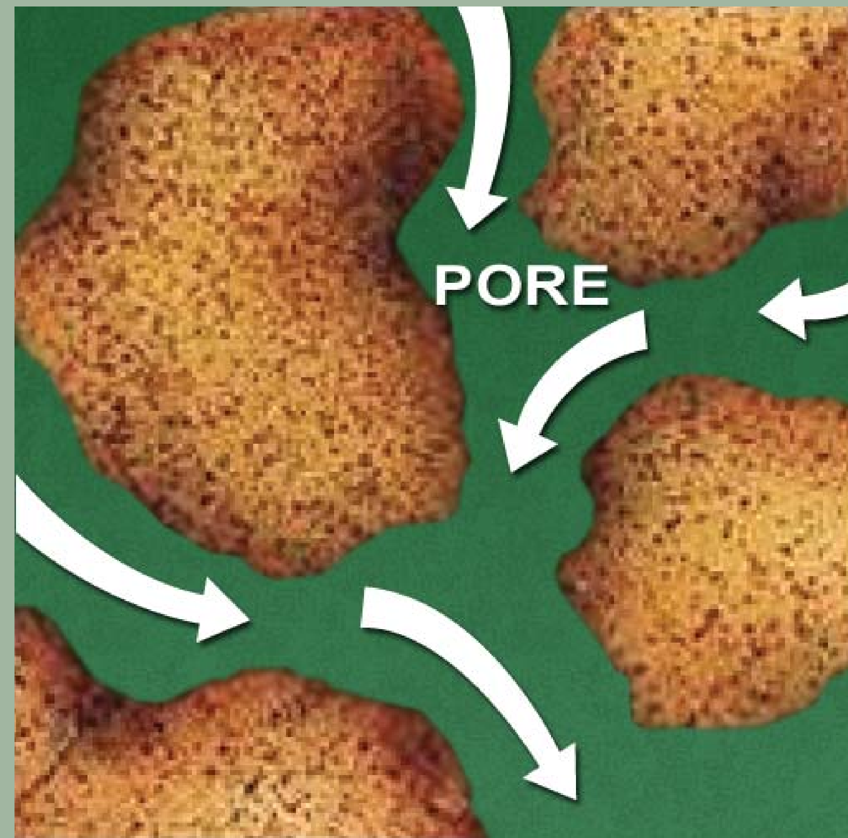
Aquifers for CAES



Succar and Williams (2008) Princeton University

Operational & Formation Parameters





Porosity, Permeability

Φ> 0.15, K>400mD favorable

Reservoir work (Aquifer)

Analysis

- A 2-D borehole/formation model was developed;
- "System" performance evaluated, Optimal formation radius = f(borehole diameter, spacing)
- Borehole diameter had only a minor influence on all the parameters including the borehole spacing and the power per borehole.

  (These differences are insignificant due to the uncertainties in the model.)
- Effect of permeability and porosity, on operational parameters assessed.

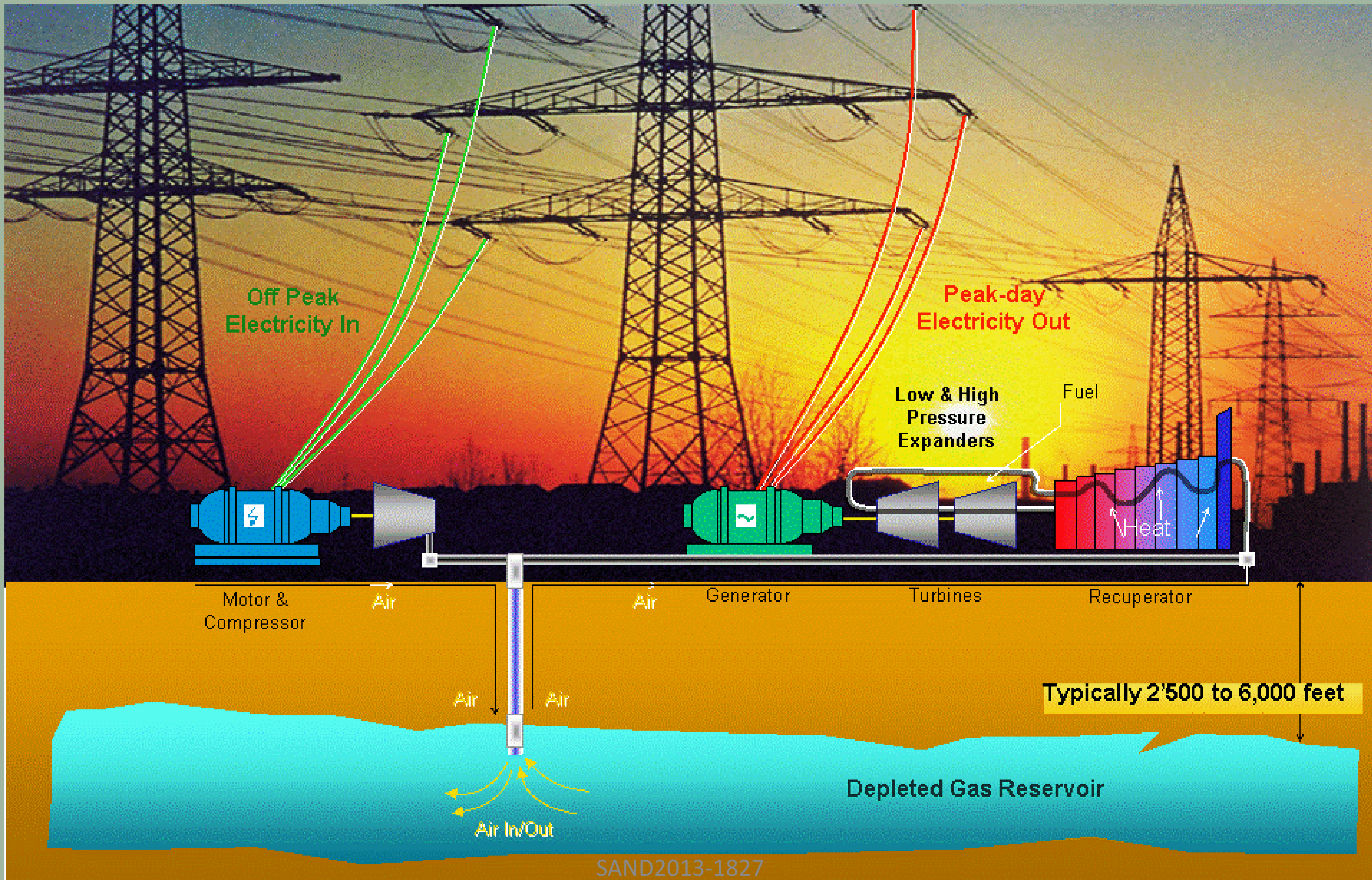
  Formation permeability much more dramatic effect than porosity changes.

  Permeability values greater than 400mD favorable

Experimental work

Near borehole effects due to pressure cycling—decrease in K observed

Depleted natural gas reservoirs



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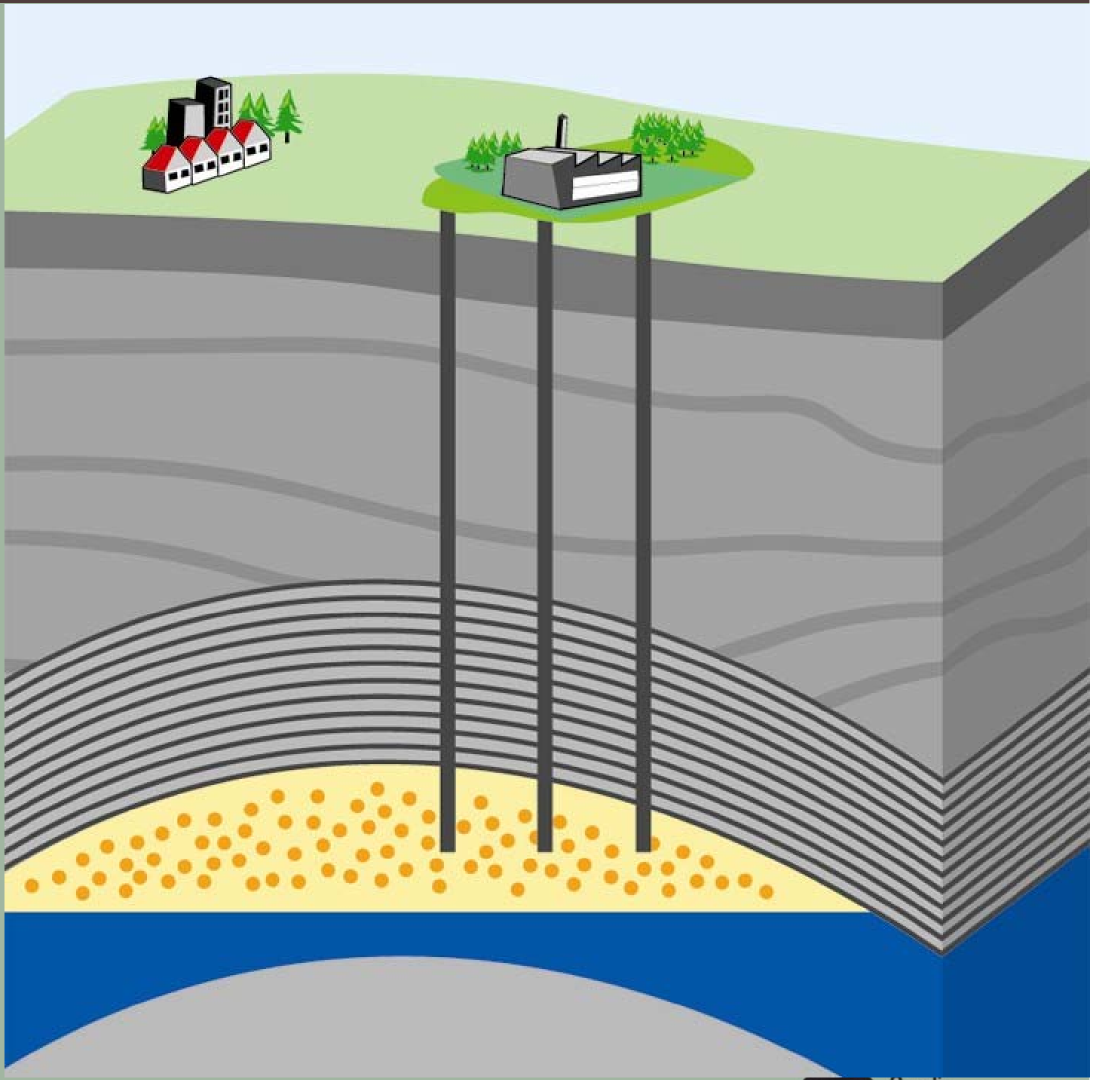
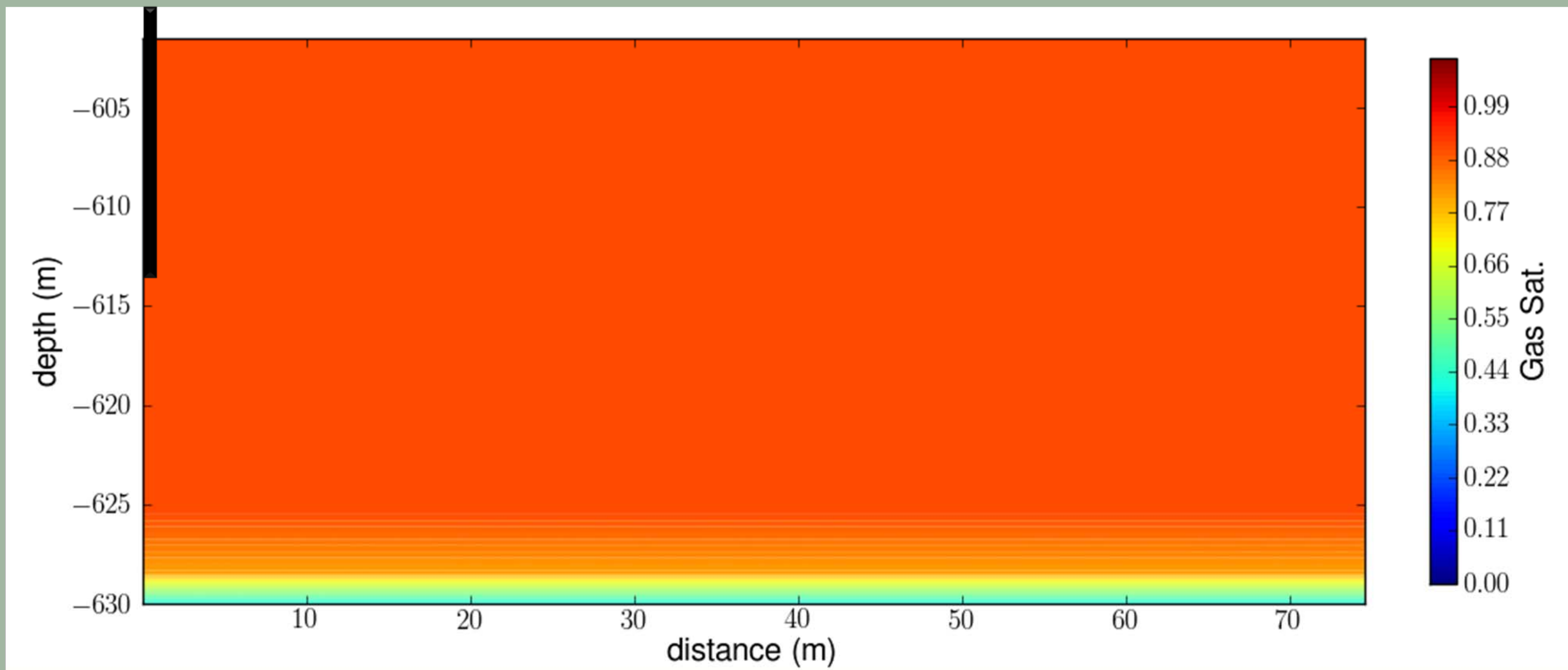
Reservoir work (DNG)

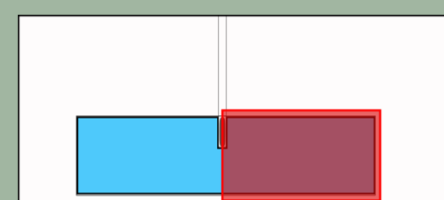
Developed numerical analysis method to model multiphase flow of air, H_2O and methane for a CAES evaluation in a depleted natural gas reservoir



The Initial Condition - Modeling a Depleted Natural Gas Reservoir



- After natural gas production, residual CH_4 is left behind
- Residual gas saturation for the given formation parameters is between 10-20% of the total porosity
- This gas phase is composed of 100% CH_4



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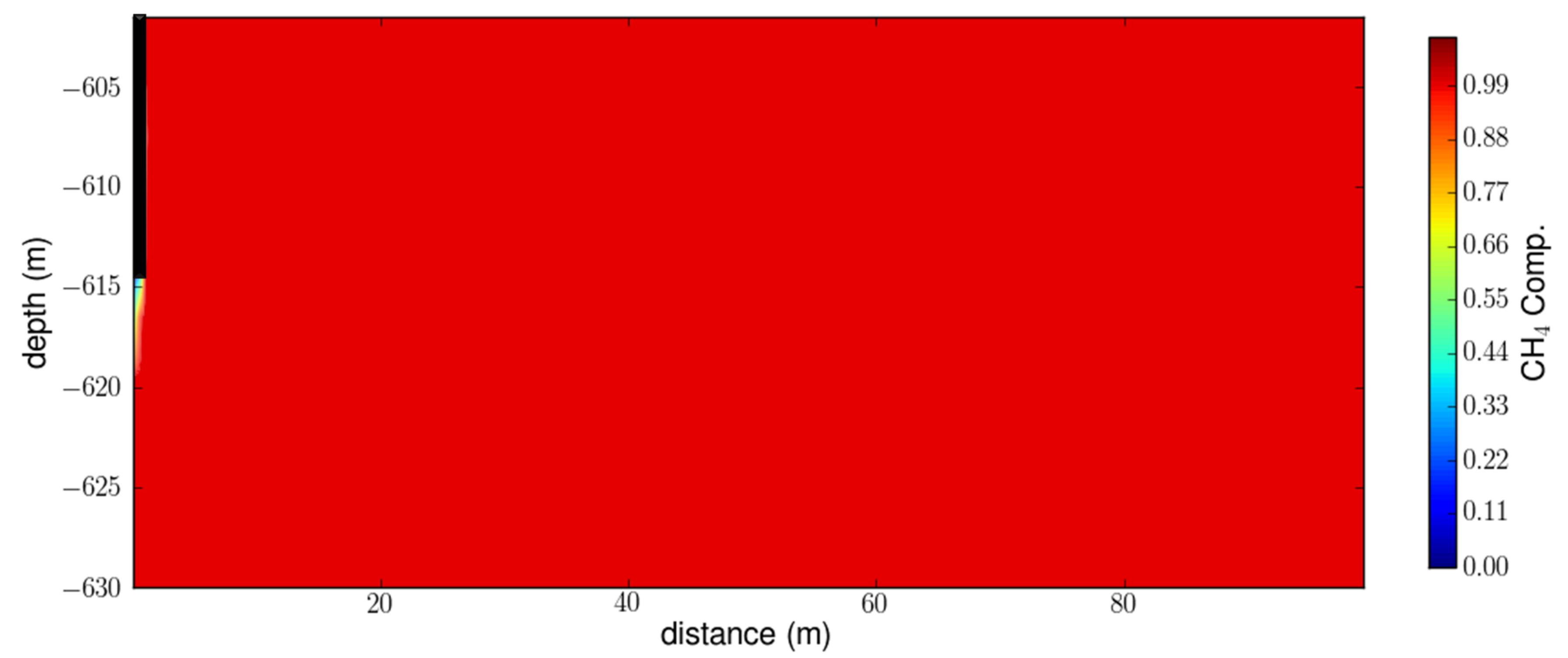
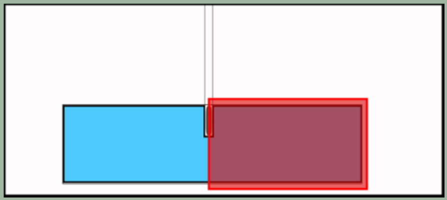
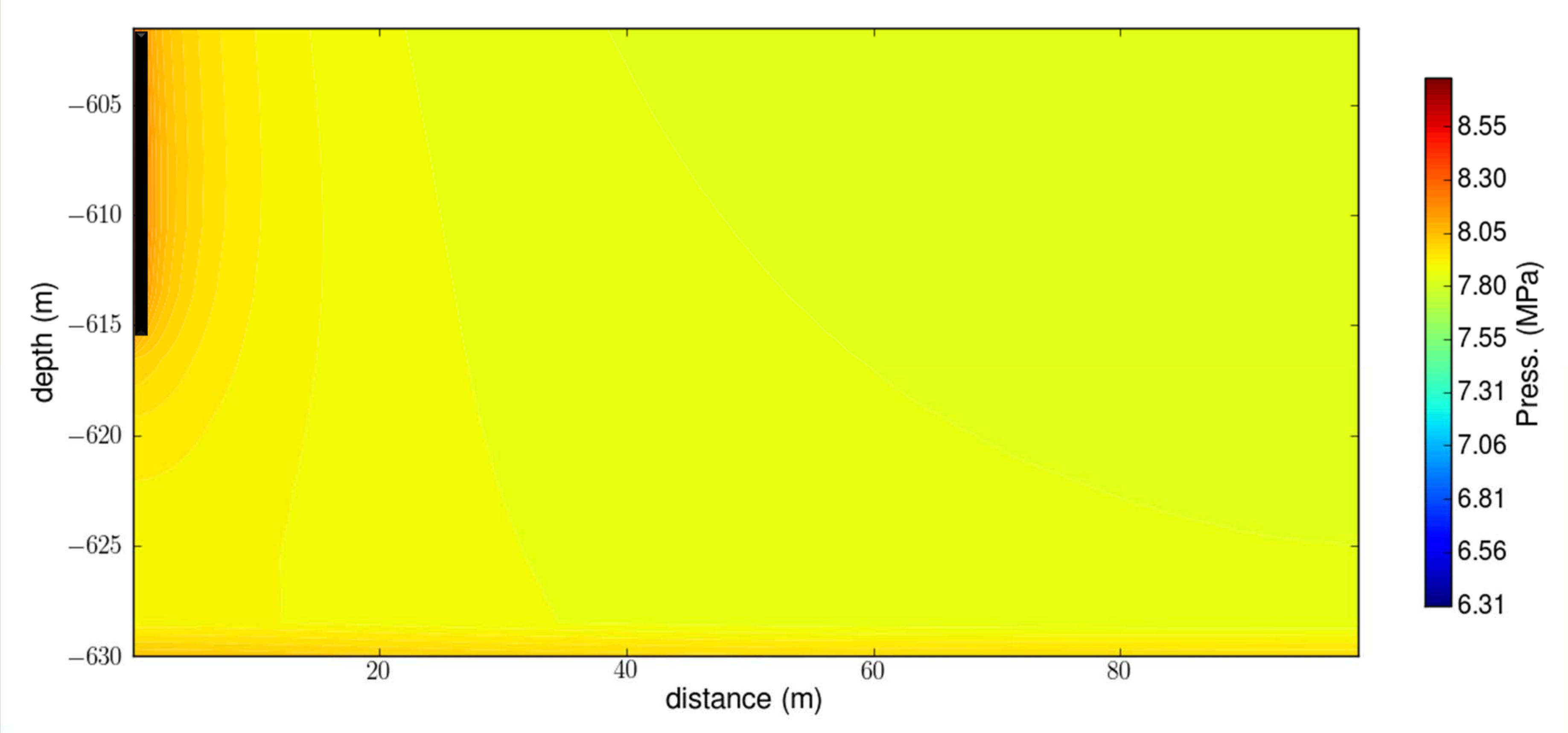
Forming an Air bubble - Gas Composition During Bubble Formation

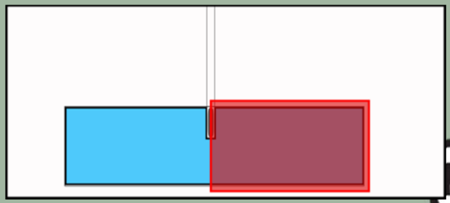


- N_2 bubble is formed and pushes the CH_4 to the fringes.
- Relatively little mixing during bubble formation.
- N_2 rich bubble next to bore



Reservoir Pressure During Cycling





Challenges

- Geology
- Heterogeneity

Depleted gas reservoir

- What does depleted mean?
- At atmospheric pressure?
  - What is the residual natural gas composition?
    - Why is this important?
      - » Heavy hydrocarbons change the ignition window and decrease the ignition temperature

Mitigation & Safety: Results & Conclusions

- Purge reservoir before use
- Low pressure air cycling below UFL to remove gas (~90 psi)
- Never draw down air below the LFL (370 psi)
- Insure no surface breach if ignition occurs (sufficient overburden)
- Monitor NG content entering surface equipment
- In-situ gas monitor
- Further study required
  - Buoyancy issues, etc.

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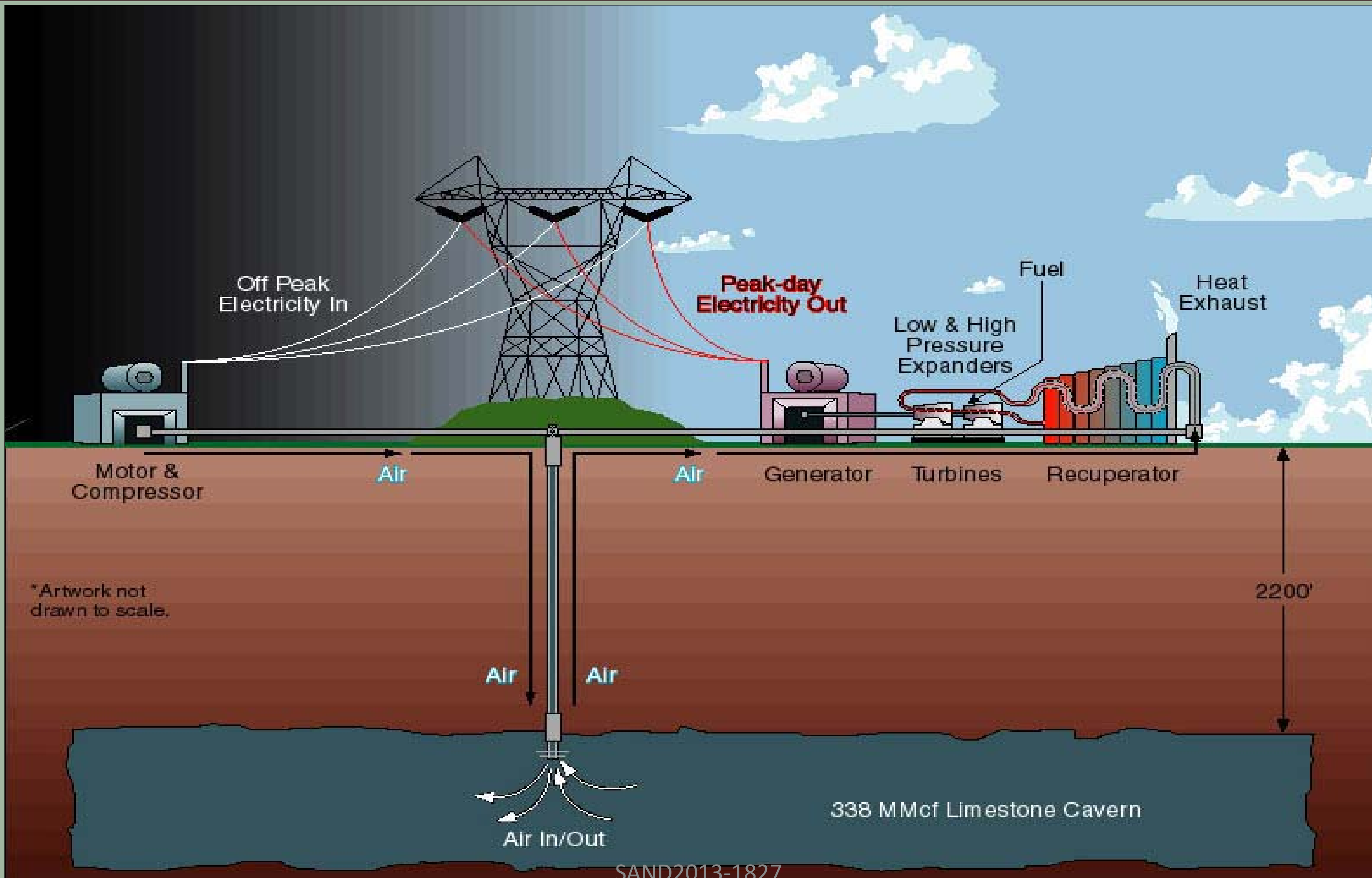
Mines



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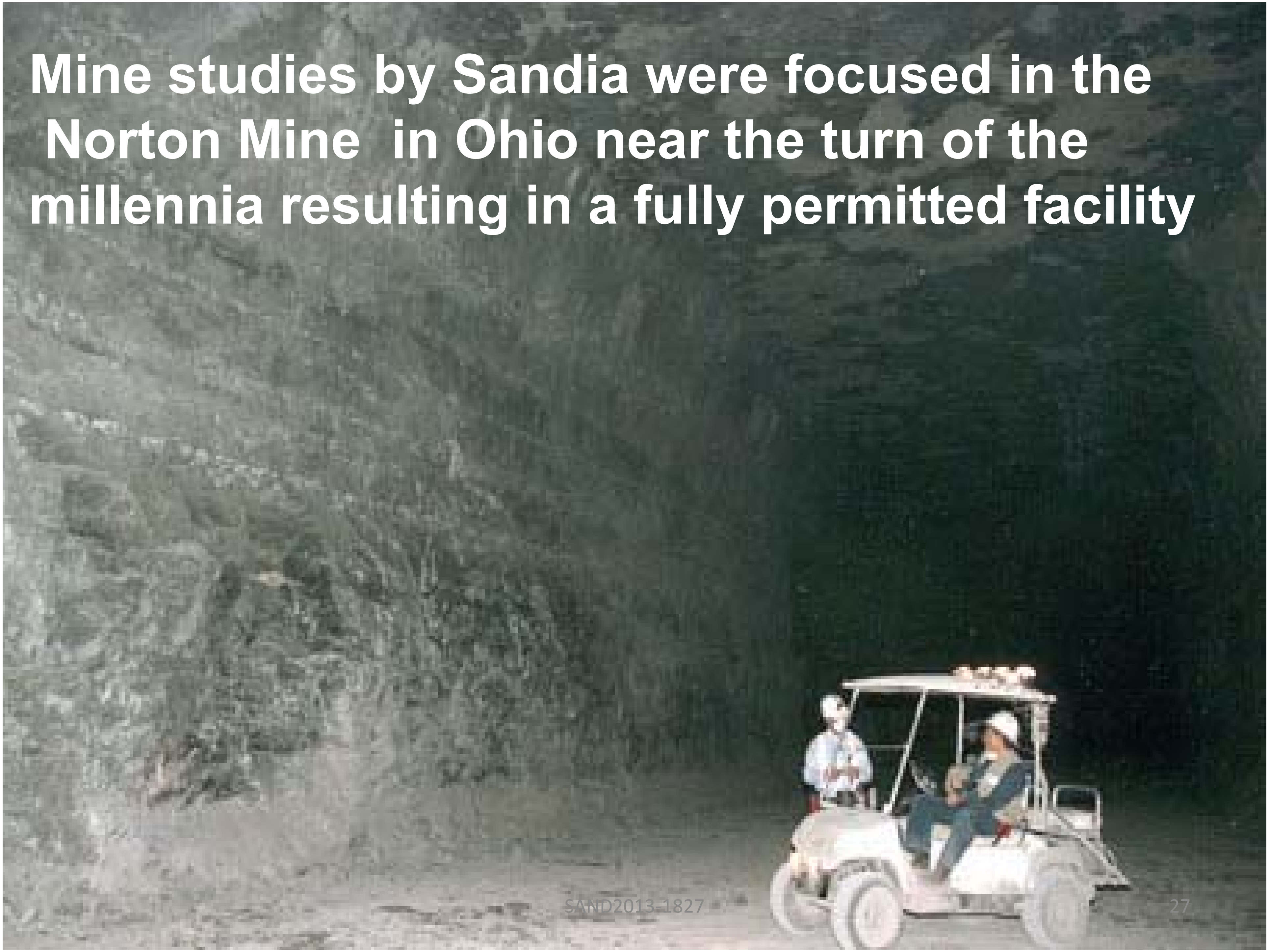
Laboratories

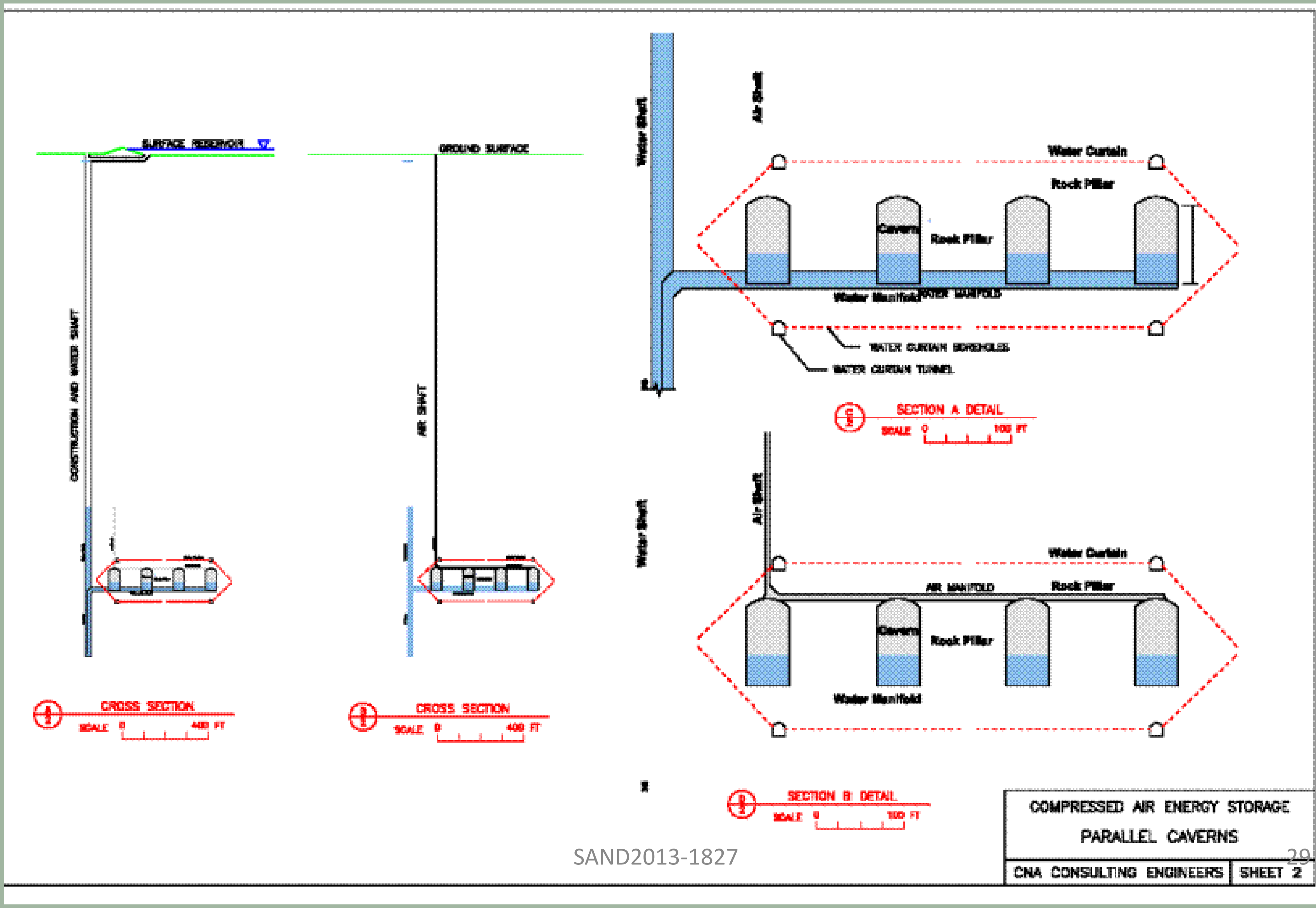
Mine studies by Sandia were focused in the Norton Mine in Ohio near the turn of the millennia resulting in a fully permitted facility



Mines

- Potential for existence of significant underground volumes
- Potential for *in situ* characterization
- Potential for recorded history
- Often a conflict between desired use and development history (maximize extraction)
- Often good electrical connections
- Beneficial use for old mines
- Flooding potential
- Environmental
- Water curtain technology deployment

Mined Rock Cavern in Granite



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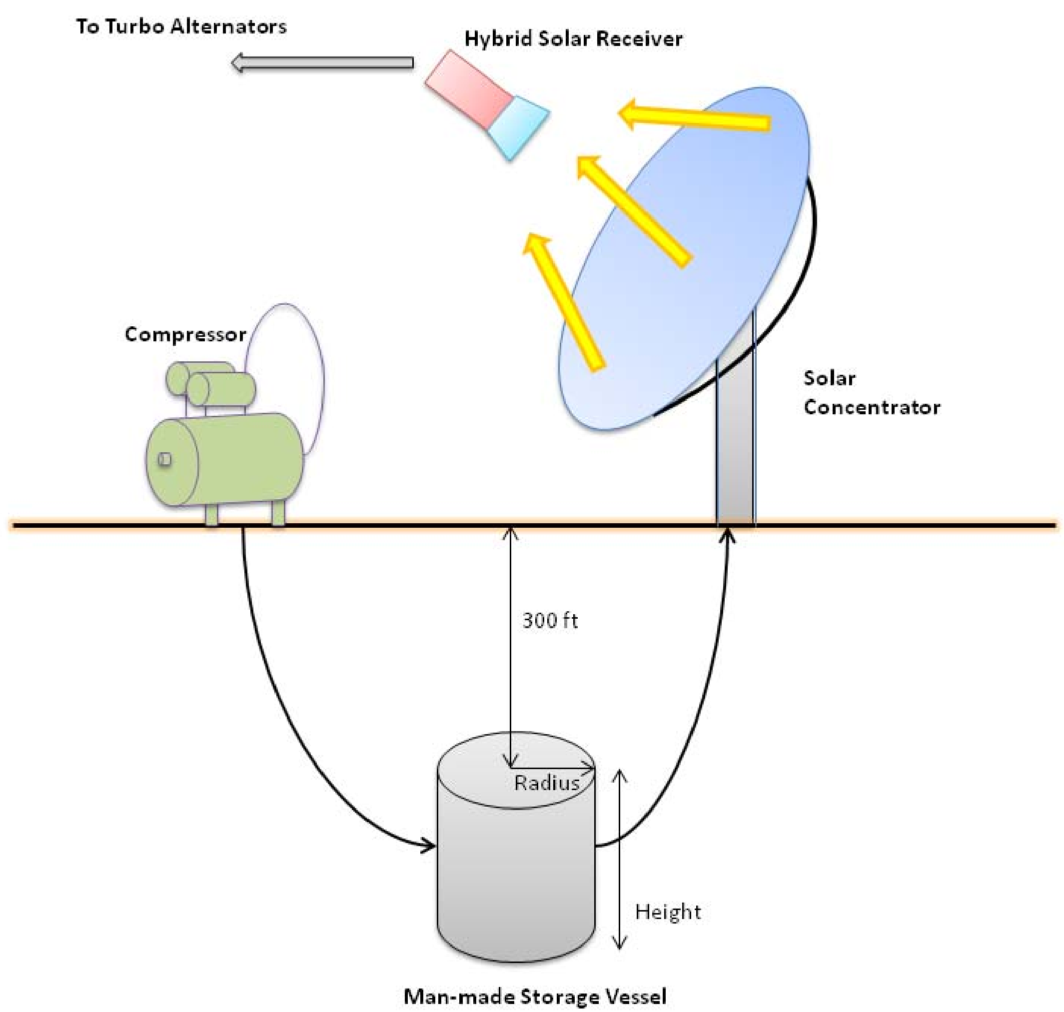
Mined rock w/ water curtain

Table Error! No text of specified style in document.**-1. Cost Summary**

WBS	Item	Quantity	Unit Cost	Cost
1.0	**Land Acquisition**			
1.1	Surface Land and Underground Rights	1		
2.0	**Surface Costs**			
2.1	Surface Site Work	1		
2.2	Surface Infrastructure	1		
2.3	Water Pond and Connections	1		
2.4	Air Piping	1		
3.0	**Caverns**			
3.1	Cavern	8		
3.2	Cavern cross cut	7		
3.3	Main shaft station	1		
3.4	Water curtain shaft station	1		
3.5	Crew room	1		
3.6	Equipment room	1		
3.7	Fuel room	1		
4.0	**Drifts and Manifolds**			
4.1	Access Tunnel	1		
4.2	Access Tunnel Connection	2		
4.3	Water Manifold	1		
4.4	Air Manifold	1		
4.5	Water Curtain Manifold	1		
4.6	Water Curtain Manifold Incline	2		
4.7	Lower Level Water Curtain Tunnel	2		
4.8	Water Curtain Tunnel	4		
5.0	**Shafts**			
5.1	Construction Shaft	1		
5.2	Water Shaft	1		
5.3	Air Shaft	1		
5.4	U Tube	1		
6.0	**Additional Items**			
6.1	Water Curtain Drillholes	758		
6.2	Bulkheads	4		
7.0	**Permitting, Fees and Professional Services**			
7.1	Permitting	1		
7.2	Site Investigation, Design, Construction Services	1		
Estimated Construction Budget before Contingency				
Contingency at 0.3				
Total Estimated Construction Budget (2011$'s)				

Solar Gen System with supplemental storage



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Multiple options available using standard structural design methods

Maximum pressure: 350 psi

Pressure vessel volume: 24000 m3

Depth to vessel top: 300 ft

Reinforced concrete vessel

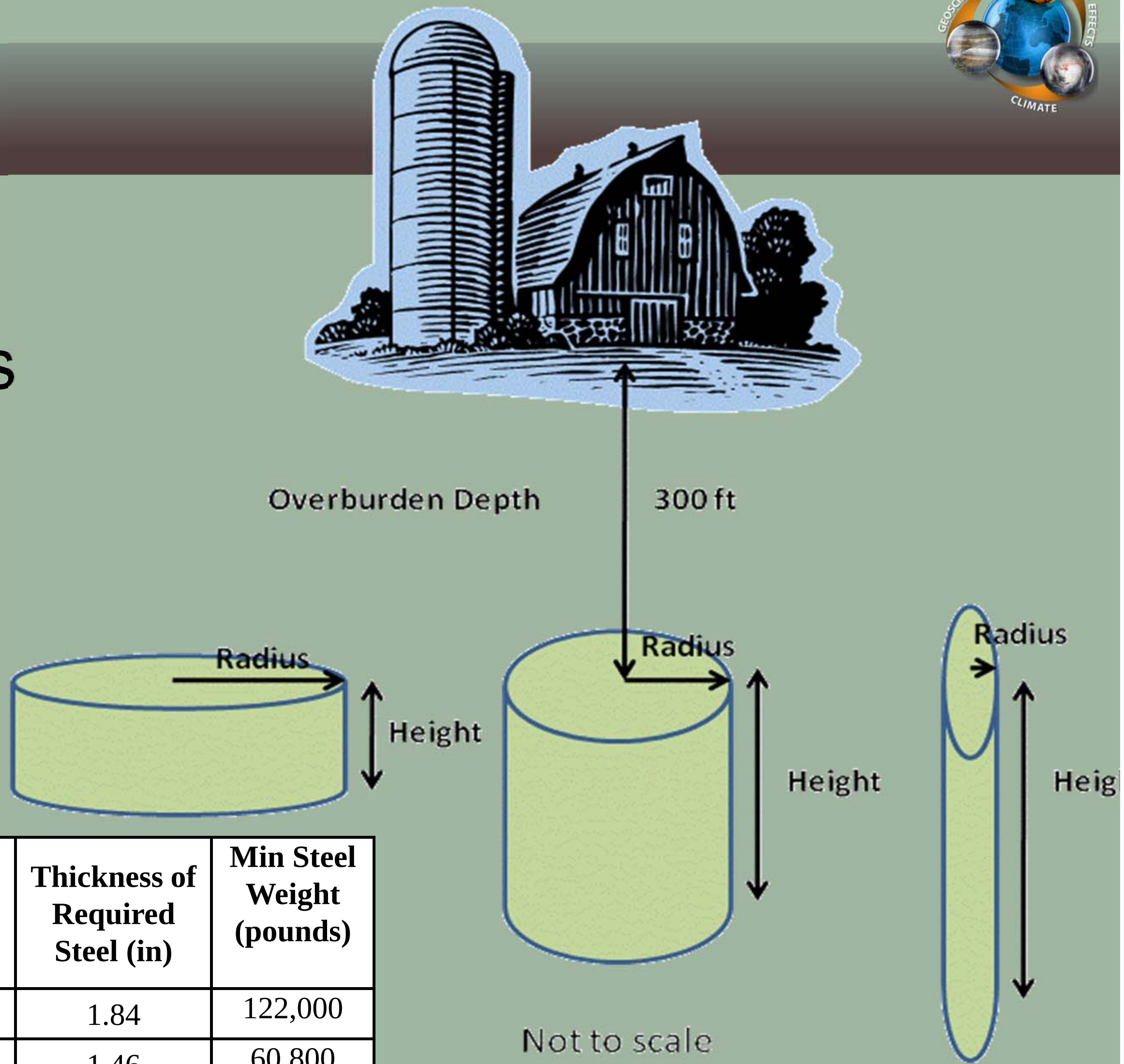
Prestressed reinforced concrete vessel

Steel vessel

Reinforced concrete (with or without prestressing) with a steel liner

Buried Reinforced Concrete Containers

350 psi
~24000 m^3



Height/Radius Ratio	Radius (m)	Height (m)	Concrete volume (m^3)	Thickness of Required Steel (in)	Min Steel Weight (pounds)
1	19.69	19.69	1,900	1.84	122,000
2	15.63	31.26	2,400	1.46	60,800
8	9.85	78.78	3,900	0.92	15,200
16	7.82	125.05	4,900	0.73	7,600
24	6.83	163.87	5,700	0.64	5,100
32	6.20	198.5	6,300	0.58	3,800

Recent Underground CAES R&D

- Underground Concrete Storage Vessels (for CAES) (Akin & Bauer, 2011) Solar Program DOE EERE
- Compressed Air Energy Storage in Hard Rock Feasibility Study (Bauer, Gaither, Webb, CNA, in prep) Wind Program DOE EERE
- Potential Hazards of Compressed Air Energy Storage in Depleted Natural Gas Reservoirs, Grubelich, Bauer, & Cooper, SAND2011-5930
- Potential Effects of Compressed Air Energy Storage on Microbiology, Geochemistry, and Hydraulic Properties of Porous Aquifer Reservoirs", Kirk, Altman, & Bauer SAND2010-4721
- Borehole and Formation Analyses to Support CAES Development in Reservoirs, S Webb SAND2011-5930
- Thermomechanical Model Development for CAES in Salt Caverns, 2012, M. Martinez, J. Holland, S. Bauer, P Hopkins, A Rinehart, Sandia National Laboratories, SAND report in prep
- Pore pressure cycling effects in a sandstone, 2012, S. Bauer, Sandia National Laboratories, SAND report in prep
- Formation Analysis for CAES in Depleted Natural Gas Reservoirs, 2012, P. Gardner, Sandia National Laboratories, SAND report in prep
- Compressed Air Energy Storage in Hard Rock Feasibility Study, 2012, S. Bauer, S. Webb, K. Gaither, Sandia National Laboratories , December 2012, SAND2012-0540
- Permeability and heterogeneity restrain compressed air energy storage in the Mount Simon Sandstone, Dallas Center structure, Iowa, 2012, J. Heath, and S. Bauer, Sandia National Laboratories, SAND report in prep
- Elasto-Plastic Constitutive Behavior in Three Lithofacies of the Cambrian Mt. Simon Sandstone, Illinois Basin, USA, 2012, T. Dewers, P. Newell, S, Broome, J. Heath, and S. Bauer, Sandia National Laboratories, SAND report in prep

thanks

Questions?

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